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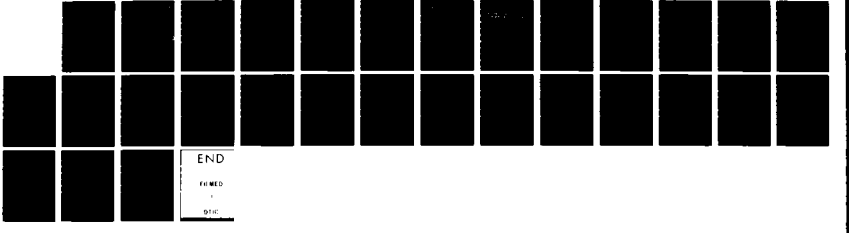

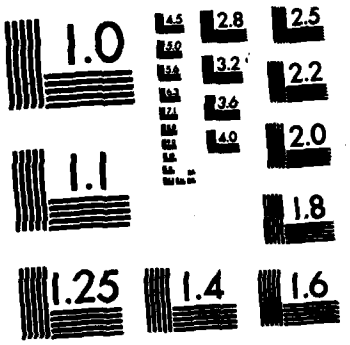

ION IMPLANTATION DEFECTS IN SILICON AND THE PERFORMANCE OF MICRON AND SUBMICRON DEVICES

FINAL REPORT

B. G. STREETMAN K. HESS

JANUARY 31, 1983

U. S. ARMY RESEARCH OFFICE

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We report investigations of hot electron effects in heterojunction layers, studies of laser annealing and ion implantation, and a general study of electronic transport in small devices.

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1. Short Description of Progress

During the period of this contract, 22 manuscripts (abstracts attached) were published or submitted for publication. The manuscripts concern real space transfer and electronic transport in submicron structures, modelling of small devices, and material research with laser and electron beam annealing. We have submitted 6 reports and descriptions of our progress before. Here we only attach a complete collection of all abstracts and papers which have been published or submitted for publication. Major progress has been made in the areas of:

(i) laser and electron beam annealing

(ii) theory of resonance scattering

(iii) modelling of small devices

(iv) studies of ultrasmall dimensions (heterolayers and superlattices). Here we demonstrated experimentally the concept of real space transfer.

2. Ph.D. and Master's Theses Finished During the Course of This Work

(a) Master's Theses:

K. Byerly	(M.S., 1981)
R. DeJule	(M.S., 1982)
H. Kafka	(M.S., 1980)
B. Lee	(M.S., 1982)
P. Martin	(M.S., 1981)
J. Y. Tang	(M.S., 1980)

(b) Ph.D. Theses:

A. Bhattacharyya	(Ph.D., 1981)
K. Soda	(Ph.D., 1980)

(c) The theses and work has been supervised by:

B. G. Streetman	Principal Investigator
K. Hess	Principal Investigator

3. Publications

A. Bhattacharyya and B. G. Streetman, "Theoretical considerations regarding pulsed CO_2 laser annealing of silicon," Solid State Communications 36, 671 (1980).

K. Hess and N. Holonyak, Jr., "Hot electrons in layered semiconductors," Physics Today, October 1980.

T. Glisson, J. R. Hauser, M. A. Littlejohn, K. Hess, B. G. Streetman, and H. Shichijo, "Monte Carlo simulation of real-space electron transfer in GaAs-AlGaAs heterostructures," J. Appl. Phys. 51, 5445 (1980).

M. Keever, H. Shichijo, K. Hess, S. Banerjee, L. Witkowski, H. Morkoç, and B. G. Streetman, "Measurements of hot-electron conduction and real-space transfer in GaAs-$Al_xGa_{1-x}As$ heterojunction layers," Appl. Phys. Lett. 38, 36 (1981).

A. Bhattacharyya and B. G. Streetman, "Dynamics of pulsed CO_2 laser annealing of silicon," J. Phys. D: Appl. Phys. 14, L67 (1981).

J. Y. Tang and K. Hess, "Real space transfer noise in buried-channel devices," IEEE Trans. Elec. Dev. ED-28, 285 (1981).

H. J. Kafka and K. Hess, "A carrier temperature model simulation of a double-drift IMPATT diode," IEEE Trans. Elec. Dev. ED-28, 831 (1981).

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A. Bhattacharyya, V. Iyer, B. G. Streetman, J. E. Baker, and P. Williams, "Electrical activation and impurity redistribution during pulsed laser annealing of BF_2^+ implanted amorphized silicon," IEEE Trans. CHMT CHMT-4, 425 (1981).

M. Keever, T. Drummond, K. Hess, H. Morkoç, and B. G. Streetman, "Time dependence of current at high electric fields in $Al_xGa_{1-x}As$-GaAs heterojunction layers," Elec. Lett. 17, 93 (1981).

K. Hess, "Lateral transport in superlattices," Proc. 3rd Int'l. Conf. on Hot Electrons in Semiconductors, Montpellier, France (1981).

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A. Bhattacharyya, B. G. Streetman, and K. Hess, "Comments on the plasma annealing model to explain the dynamics of pulsed laser annealing of ion-implanted silicon," J. Appl. Phys. 53, 1261 (1982).

P. D. Coleman, J. Freeman, H. Morkoç, K. Hess, B. G. Streetman, and M. Keever, "Demonstration of a new oscillator based on real-space transfer in hetero-junctions," Appl. Phys. Lett. 40, 493 (1982).

K. K. Mon and K. Hess, "Resonance impact ionization in superlattices," Solid-State Elec. 25, 491 (1982).

O. F. Sankey, J. D. Dow, and K. Hess, "Theory of resonant scattering in semi-conductors due to impurity central-cell potentials," Appl. Phys. Lett. 41, 664 (1982).

K. Hess, "Aspects of high field transport in semiconductor heterolayers and semiconductor devices," in Advances in Electronics and Electron Physics, ed. by P. W. Hawkes, vol. 59, p. 239 (New York: Academic Press, 1982).

K. Hess, "Electronic transport in GaAs-GaAlAs heterolayers and high mobility transistors," Philadelphia meeting of the American Physical Society, November 3-5, 1982 (invited paper).

K. Hess, "Electron transport in heterojunctions and superlattices," Proceed-ings of the 16th International Conference on the Physics of Semiconductors, 1982 (invited paper).

S. Banerjee and B. G. Streetman, "Theoretical and experimental study of swept line electron beam annealing of semiconductors," (submitted to the Journal of Applied Physics).

S. K. Banerjee, R. Y. Tong, B. Lee, R. Y. DeJule, and B. G. Streetman, "Annealing studies of alterally seeded recrystallized silicon on silicon dioxide. I. Phosphorus implants," (in preparation).

S. K. Banerjee, B. Lee, R. Y. Tong, R. Y. DeJule, and B. G. Streetman, "Annealing studies of laterally seeded recrystallized silicon on silicon dioxide. II. Boron implants," (in preparation).

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THEORETICAL CONSIDERATIONS REGARDING PULSED CO_2 LASER ANNEALING OF SILICON*

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(Received 8 July 1980 by A. A. Maradudin)

We present a calculation of the surface temperature and investigate the "thermal runaway" phenomenon during pulsed CO_2 laser (λ = 10.6 μm) annealing of silicon. In calculating the temperature variation of free carrier absorption in n-Si, we have taken into account acoustic deformation potential scattering, optical deformation potential scattering, and ionized impurity scattering. The deformation potentials are adjusted to fit the experimentally observed values at 300°K. Also, we discuss the contribution of free carrier absorption during annealing with a Nd:glass laser (λ = 1.06 μm).

Recently there have been wide applications of pulsed and cw lasers in the annealing of ion implanted Si for device fabrication. In particular, CO_2 lasers are being used for this purpose[1,2] because of their considerable power output, large beam spot size, easy installation, and consequent industrial application. However, data has not been previously available on the temperature variation of free carrier absorption in Si, upon which these applications depend.

This paper presents results from a quantum mechanical calculation of the temperature variation of the free carrier absorption coefficient for n-type Si at 10.6 μm. Here we report for the first time the application of the temperature dependent absorption coefficient to investigate the rise in surface temperature leading to thermal runaway during CO_2 laser annealing of Si. We have calculated the power density required to initiate the thermal runaway situation. Our results are in good agreement with those observed experimentally.[1,2] In calculating the absorption coefficient we have adjusted the deformation potentials such that the calculated values agree with the available experimentally obtained values[3,4] at 300°K. It is well known that at 10.6 μm the absorption mechanism in Si is primarily due to free carriers, with a small contribution due to multiphonon excitations. The variation of absorption coefficient with temperature provides insight into the mechanism by which laser power couples into the material. We find that the absorption coefficient increases rapidly with temperature, resulting in a "thermal runaway" situation for large power densities. This can lead to melting of the implanted layer as observed experimentally, and subsequent liquid phase epitaxial regrowth[2] during pulsed CO_2 laser annealing. The calculations also explain the mechanism by which temperature increases to a sufficient value for a solid phase epitaxial regrowth during cw CO_2 laser annealing.[1]

We calculate the contributions from the acoustic deformation potential scattering (α_{ac}), optical deformation potential scattering (α_{op}), and ionised impurity scattering (α_{io}), and add them together to give the total free carrier absorption coefficient (α)[5] as a function of temperature from 300°K to 1685°K (the melting point of Si):

$$\alpha = \alpha_{ac} + \alpha_{op} + \alpha_{io} \qquad (1)$$

We have taken into consideration the contribution from both the electrons and holes for completeness, although the holes contribute little for n-type Si. The data presented are for the case of thermal equilibrium with the electron temperature equal to the lattice temperature ($T_e = T$).

The free carrier absorption coefficient for the acoustic deformation potential scattering is given by

$$\alpha_{ac} = \frac{\mu_o c\, 2^{3/2}\, n e^2 \epsilon_{ac}^2 (m^* k_B T)^{1/2}}{\sqrt{\kappa}\, 3\pi^{3/2} \hbar^3 c_\ell \omega} \left(\frac{T}{T_e}\right)^{1/2} \sinh\left(\frac{\hbar\omega}{2k_B T_e}\right) K_2\left(\frac{\hbar\omega}{2k_B T_e}\right) \qquad (2)$$

where $\mu_o c$ = 377 ohm, n is the free carrier concentration, ϵ_{ac} is the acoustic deformation potential constant, κ is the dielectric constant of the material, c_ℓ is the longitudinal

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Hot electrons in layered semiconductors

The size of semiconductor devices has decreased so much that classical treatments of semiconductor physics become invalid and effects involving supra-thermal electrons take on a new importance.

Karl Hess and Nick Holonyak, Jr

As electronic systems—and especially computers—are used more and more widely in almost all areas of endeavor and daily life, the semiconductor technology on which they are based is being pushed to ever larger-scale integration and ever greater miniaturization. As the devices get smaller, and smaller, new problems (and maybe new opportunities) appear.[1]

One consequence of the reduction in size is that the fields accelerating electrons and holes through the crystal become very large, so that the carriers acquire large kinetic energies. The equations of motion for an energetic electron in the lattice can be appreciably different from Newton's laws; its (inertial) mass can, for example, appear to be infinite or even negative. This has nothing to do with relativistic effects but is due to Bragg reflection. The non-linearity of the equation of motion is illustrated in figure 1, which shows lines of equal energy in momentum space (k-space) for the semiconductor gallium arsenide.[2] For a free particle, these lines would be circles, as they are near the origin in figure 1, because the energy depends only on the magnitude of the momentum. The complicated shapes of the curves for large k indicates that the relation between energy and momentum is anisotropic and not quadratic. Electrons then do not necessarily move in the direction of the electric field and their average speed is not simply proportional to the field strength; that is, Ohm's law breaks down. We shall discuss this point more extensively later.

To illustrate the reduction in size that has accompanied the progress of semiconductor technology, we show in figure 2 the original point-contact transistor and a modern layered quantum-well heterostructure. (We should point out, though, that the point-contact transistor was a much smaller device than the junction transistors that were subsequently most widely used in practical devices.)

As we mentioned, the electric fields in small devices can become very large. If we assume that operating voltages of semiconductor devices are around 5 V, then the maximum electric fields in a typical device of twenty years ago was on the order of 10–100 V/cm. In a present-day integrated circuit the average fields are 10^3 V/cm and maximum fields are an order of magnitude larger. At such field strengths silicon and germanium become non-Ohmic at room temperature.[3] Fields on the order of 10^5 V/cm are encountered between neighboring gates of charge-coupled devices and in quantum-well layered devices. Such large fields may also be approached in the very-large-scale integrated circuits that are now being developed.

At fields larger than 1000 volts/cm the charge carriers in a semiconductor are accelerated far above their thermal-equilibrium energy (given by the lattice temperature). Under these circumstances so-called "hot-electron effects" become important and many of the familiar concepts of semiconductor physics lose their validity. In this article we will discuss some of the effects that will be important in future very-large-scale integrated circuits and in optoelectronic devices.

The authors are professors of Electrical Engineering at the University of Illinois, Urbana. Karl Hess is also a member of the Coordinated Science Laboratory and Nick Holonyak is also a member of the Materials Research Laboratory at the University.

Hot electrons

As electrons move through the crystal lattice, they interact both with each other and with the lattice. In electronic devices, the applied electric field supplies energy to the electrons. If electron–electron collisions randomize the carrier energy, one can define a temperature for the electrons even for very high fields. This temperature T_e is always higher than the temperature of the crystal lattice T_L. The difference between T_e and T_L depends strongly on the electric field (actually on the square of the field because reversal of the field must not lead to negative temperatures) and on the details of how the electrons lose their energy. In all practical cases the electrons lose their energy to lattice vibrations. We thus have a picture of a highly mobile fluid at high temperature (the "electron gas") moving through the cooler crystal lattice and losing energy to it.

We know that conducting wires begin to glow if too much energy is transferred from the electron gas to the crystal lattice. We would like to emphasize, however, that even if the lattice remains cold (a situation that often can be arranged), the temperature of the electrons can be exceedingly high and cannot be controlled by any cooling mechanism (other than the slow heat loss to the lattice). A typical example would be a piece of silicon, let us say, to which an electric field of 2×10^4 V/cm is applied; the electron temperature rises to 1000 K no matter what the

Monte Carlo simulation of real-space electron transfer in GaAs-AlGaAs heterostructures

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(Received 13 March 1980; accepted for publication 11 June 1980)

The Monte Carlo method has been used to simulate electron transport in GaAs/AlGaAs heterostructures with an electric field applied parallel to the heterojunction interface. The simulations indicate that a unique physical mechanism for negative differential conductivity is provided by such layered heterostructures, which is analogous in many respects to the Gunn effect. This mechanism has been termed "real-space electron transfer" since it involves the transfer of electrons from a high-mobility GaAs region to an adjacent low-mobility AlGaAs region as the applied electric field intensity is increased. The simulations further indicate that the important details of the resulting velocity-field characteristics for these layered heterostructures can be controlled primarily through material doping densities, layer thicknesses, and the material properties of the individual layers. Thus, the phenomenon of real-space electron transfer potentially provides the ability to "engineer" those basic material properties which influence the performance of negative resistance devices.

PACS numbers: 72.20.Jv, 72.80.Ey,

I. INTRODUCTION

In a recent paper[1] a new mechanism for obtaining negative differential conductivity in layered heterostructures was described. This mechanism is based on the transfer of hot electrons from high-mobility GaAs layers sandwiched between adjacent low-mobility $Al_xGa_{1-x}As$ layers. The resulting negative differential conductivity is analogous to the Gunn effect, except that the electrons are transferred in real space rather than in momentum space.

To properly describe real-space electron transfer, it is necessary to account for the scattering mechanisms encountered by electrons being transported at high kinetic energies in the potential well in the GaAs, which exists due to the conduction band discontinuity between GaAs and AlGaAs. A mechanical analogy to real-space transfer is provided by the example of a ball rolling down a chute. The ball will stay in the chute if its kinetic energy remains small. However, if the ball gains adequate kinetic energy, then an obstacle can scatter the ball out of the chute. A similar effect occurs in a layered heterostructure where electrons drift in the potential well under the influence of a high electric field. If the mobilities inside and outside the well can be controlled, then the transfer of electrons from the well can be used to control the current-voltage characterisitcs of the heterostructure device. If the mobility outside the well is much lower than that inside, the effect results in a negative differential conductivity.

In the previous paper,[1] the real-space transfer effect was examined on the basis of "thermionic emission currents"; that is, the densities of electrons inside and outside the well were calculated by balancing the Richardson currents.[2] In these calculations the layers were treated independently, and energy exchange between the layers was not considered. The energy distribution of the electrons in both layers was assumed to be Maxwellian, with the GaAs at an elevated temperature T_e and with the temperature in the $Al_xGa_{1-x}As$ assumed to be equal to the lattice temperature T_L. This model has four essential deficiencies: (i) It is well known that at high electric fields the energy distribution functions in polar semiconductors are highly non-Maxwellian. (ii) There is an energy exchange between the layers because energetic carriers are flowing out of the GaAs and cold carriers are returning. (iii) The model does not account for electron temperature gradients or electron-electron interactions. (iv) The complicated band structure of the multilayer heterojunctions (e.g., the role of the L minima in the two materials) was not considered.

It is possible to include (ii) and (iii) in a simple theory using the method of moments.[3] This type of calculation is described elsewhere.[4] The only calculation capable of simultaneously including (i), (ii), and (iv), however, is a Monte Carlo calculation. The purpose of this paper is to describe the results of a Monte Carlo study of real-space transfer in GaAs/AlGaAs layered heterostructures. The Monte Carlo calculations predict a negative differential conductivity for properly chosen heterostructures. The advantage of this negative resistance mechanism over the normal Gunn effect is that all the essential materials parameters can be "engineered". For example, the peak-to-valley ratio can be controlled by the layer width and mobility ratio (including modulation doping[5]), the onset of the negative differential resistance can be controlled by the Al mole fraction (barrier height), and finally the speed of the device can be controlled by the layer thicknesses. We also show that the real-space transfer effect should occur well before the Gunn effect (k-space transfer) for junction barrier heights of approximately 200 meV in GaAs/$Al_xGa_{1-x}As$ heterostructures.

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Measurements of hot-electron conduction and real-space transfer in GaAs-$Al_xGa_{1-x}As$ heterojunction layers

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Measurements of the current-voltage characteristics of GaAs-$Al_xGa_{1-x}As$ heterojunction layers are reported. The experimental results are consistent with the idea of real-space transfer of the electrons out of the GaAs into the $Al_xGa_{1-x}As$ under hot-electron conditions. Current saturation and negative differential resistance are observed as predicted by Monte Carlo simulations.

PACS numbers: 72.20.Ht, 73.40.Lq

Electronic transport in semiconductor heterojunction layers has attracted considerable interest since Dingle and co-workers verified mobility enhancement in modulation-doped structures.[1] Such enhancement occurs when electrons leave their parent donors (e.g., in the $Al_xGa_{1-x}As$) and transfer to a neighboring undoped layer which has a smaller band gap (e.g., GaAs). Thus the electrons will not be scattered strongly by the remote impurities (donors) and the mobility in the GaAs will be enhanced. Although there are some subtleties, including an enhanced phonon scattering rate,[2] this improved mobility is reflected by the experiments.

Theoretical investigations of high-field transport in these layers led Hess *et al.* to conclude that when a high electric field is applied parallel to the layer interfaces the inverse process takes place, namely a transfer of electrons from the GaAs layers back into the $Al_xGa_{1-x}As$ layers.[3] This process can be viewed as the thermionic emission of hot electrons, and has simple mechanical analogies.[4] A Monte Carlo simulation of the real-space trajectory of an electron for a double heterojunction of $Al_xGa_{1-x}As$ ($x = 0.17$) is shown in the inset of Fig. 1. After some reflections an electron in the GaAs layer gains enough kinetic energy from the applied electric field to move out of the potential well caused by the band-gap difference between the two materials. More exact treatments of this effect including quantum-mechanical transmission coefficients do not reveal new features for this picture.[4] The movement of the hot electrons back into the low-mobility $Al_xGa_{1-x}As$ material will of course lead to a nonlinear behavior in the current density. Figure 1 shows the current-voltage characteristic of the double-heterojunction structure shown in the inset. These results were obtained from Monte Carlo calculations.[4] The magnitude of the negative differential resistance in such a curve depends on the doping densities which control the free-carrier concentrations and mobilities in the $Al_xGa_{1-x}As$ and GaAs layers. A very high doping density in the $Al_xGa_{1-x}As$ causes a high concentration of scattering centers, which results in a very low mobility and high resistance in the $Al_xGa_{1-x}As$ and therefore can yield large peak-to-valley ratios, larger than those observed in the Gunn effect, which is based on the k-space analog of the mechanism described here.

In this letter we report measurements of the high-field characteristics of $Al_xGa_{1-x}As$ structures grown by molecular beam epitaxy (MBE). The doping density in the $Al_xGa_{1-x}As$ layers was $N_D \simeq 10^{17}$ cm^{-3} and the GaAs was not intentionally doped. The mobility in the GaAs layers was enhanced over the bulk value for equivalent doping and was typically 2×10^4 cm^2/V s at 77 K. The mobility in the $Al_xGa_{1-x}As$ layers was around 1000 cm^2/V s between 300 and 77 K. The doped $Al_xGa_{1-x}As$ layer was 1000 Å thick in all cases, whereas the GaAs layers varied in thickness from 400 Å to $\sim 1.0\,\mu$m. In some of the samples the GaAs layer was sandwiched between the doped and a second (undoped) $Al_xGa_{1-x}As$ layer. Because of the pulling force of the donors we think that the actual width of the GaAs layer is relatively unimportant, since the electrons in the GaAs will always be within 1600 Å of the doped $Al_xGa_{1-x}As$ layer. Although x was 0.17 for most of the data reported here, we have made similar measurements with x increased to 0.25. Au-Ge contacts were evaporated on top of the layer (top layer $Al_xGa_{1-x}As$) and alloyed by heating at a rate of 400 °C/min in flowing H_2 to a final temperature of 450 °C. Contacts formed in this way proved to be ohmic in most cases. The distance between the contacts was 0.065 cm and the width of the samples was about 0.1 cm. Measurements were performed using short current pulses. The measurements were taken at times between 1 and 600 ns. The samples were mounted in GR insertion units and the usual 50-Ω sampling oscilloscope x-y recorder technique was used.[5] Below we report five groups of results:

(i) Unusually strong acoustoelectric sound amplification and accompanying negative differential resistance (inset Fig. 2) was observed in some samples at 77 K at very low electric fields of about 300 V/cm having incubation times as low as ~ 3 ns. This effect did not occur at room temperature (the samples were too short) and was not observed in any of the samples for which results are reported below. A detailed report will be given in a subsequent publication.

(ii) In samples not showing the acoustoelectric effect (about 40 samples from 5 wafers) onset of current saturation or slight negative differential resistance was observed at an

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LETTER TO THE EDITOR

Dynamics of pulsed CO_2 laser annealing of silicon

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Received 23 February 1981

Abstract. We present a detailed calculation using the method of finite differences to study the dynamics of pulsed CO_2 laser annealing of ion-implanted Si. The calculations are based on a thermal melting model, taking into account the temperature dependences of all pertinent material parameters, including the absorption coefficient. We investigate the 'thermal runaway' behaviour and calculate the threshold power density to cause thermal runaway and surface melting of Si during CO_2 laser annealing.

Pulsed lasers have been successfully applied for annealing of radiation damage associated with ion implantation in Si during device fabrication. Experimentally, work has been mainly confined to laser wavelengths in the visible and near-infrared using a frequency-doubled YAG laser at $\lambda = 0.53$ μm (Surko *et al* 1979), a ruby laser at $\lambda = 0.69$ μm (Bell *et al* 1979) and a Nd:glass laser at $\lambda = 1.06$ μm (Bhattacharyya *et al* 1981). In all these lasers the spot-size of the laser beam on the Si sample was typically a few mm in diameter. Hence, to anneal a large area it was necessary to use successive overlapping pulses, leading to nonuniform crystalline quality in the overlap regions. Pulsed CO_2 lasers have the distinct advantage of having considerably larger spot-size, and are therefore very promising for laser annealing of large Si wafers commonly used in industrial production. At 10.6 μm, the absorption coefficient of amorphous silicon is much smaller than that of crystalline silicon having large donor concentration. Hence, for annealing with a CO_2 laser it is advantageous to implant the sample with a moderately high ion dose without driving the sample amorphous.

It is now well established that the physical phenomenon behind pulsed laser annealing is thermal melting leading to liquid phase epitaxial regrowth. The dynamics of pulsed laser annealing for amorphous silicon using a Nd:glass laser (Bhattacharyya *et al* 1981) and for crystalline silicon using a frequency-doubled YAG laser (Baeri *et al* 1979) have been studied in detail. We have recently calculated (Bhattacharyya and Streetman 1980) the temperature variation of the free carrier absorption in Si for a CO_2 laser and with suitable approximations have analytically investigated in the 'low temperature' region ($T < 1150$ K) the phenomenon of 'thermal runaway' during pulsed CO_2 laser annealing of Si.

In this paper we present results of calculations using the finite-difference method of solving the nonlinear heat conduction equations to investigate the phenomenon of surface melting and crystalline regrowth. The temperature variations of all the various physical parameters have been taken into full consideration to provide a predictive theoretical model. We find that the temperature dependence of the free-carrier absorption coefficient

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Real Space Transfer Noise in Buried-Channel Devices

JEFF Y. TANG AND KARL HESS, MEMBER, IEEE

Abstract—The noise due to the spilling of hot electrons out of potential wells and subsequent trapping is calculated. This noise is the real space analogy to the intervalley noise in transfer devices. Our results show that this noise can be important for heterojunction FET's and MOS devices. The Thornber formalism used in our calculation is general and applies for nonstationary cases. Results are given only for the specific case of buried-channel charge-coupled devices because for other devices this type of noise can be derived as a special case.

I. Introduction

IT HAS BEEN SHOWN in numerous papers [1]-[4] that the motion and population of electrons and holes in potential wells play a significant role in the physics of semiconductor devices. The conducting channel in MOS devices is frequently buried in a potential minimum away from the interface to avoid trapping in interface states. Ordinary surface-channel MOS devices have narrow potential wells at the Si–SiO_2 interface which lead to size quantization. The potential wells of heterostructure layers are used in numerous ways for optoelectronic devices and FET's. Modulation-doped material offers the possibility of producing potential wells with very high electron mobilities.

Under certain simplifying assumptions, which will be specified later, the electron concentration in a potential well is given by

$$N = N_0 \exp\left[e\phi/kT_e\right]. \tag{1}$$

Here N_0 is a constant concentration, ϕ is the potential, and T_e the electron temperature which is not necessarily identical with the temperature of the crystal lattice. Generally, T_e is controlled by electric fields which give rise to a drift current, and T_e can be extremely high in high electric fields (up to several thousand degrees Kelvin).

The spatial distribution of N depends on T_e as can be seen from (1). For $T_e \to \infty$, the electrons assume a constant concentration. This means, for example, that we can generate a transition from a buried-channel device to a surface-channel device by creating hot-electron conditions with high electric fields [2]. On the same basis, electrons are emitted into substrates in FET's which is also an unwelcome effect. It was shown theoretically that this effect can also be used to create negative differential resistance [3] by thermionically emitting hot electrons out of layers with high mobility to layers with low mobility.

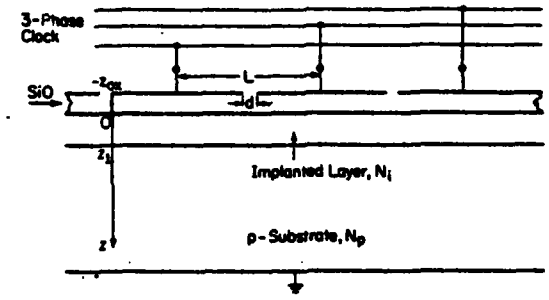

Fig. 1. The n-channel BCCD model used in our calculation with gate length $L = 5\ \mu m$, gap $d = 0.01\ \mu m$, thickness of oxide layer $Z_{ox} = 0.04\ \mu m$, implanted layer depth $Z_1 = 0.5\ \mu m$, background doping $N_p = 2.5 \times 10^{15}\ cm^{-3}$, and implantation dose of $4.0 \times 10^{12}\ cm^{-2}$.

Clearly, noise can be introduced by this hot-electron emission mechanism. In general, the noise will depend on the history of the emitted electrons, for example, on trapping subsequent to the emission process. The trapping could occur in deep levels in $Al_xGa_{1-x}As$ layers neighboring to GaAs layers or in interface states at interfaces close to a buried channel. The generation-recombination process has to be described then by a rate equation which contains the free carrier concentration N, where N is given by (1) with ϕ being the potential at the interface. A variety of situations can arise in various devices. As an example, we perform the calculation for a buried-channel charge-coupled device. We made this choice because of the nonstationary character of electron transport in this device. Stationary problems can be obtained from our treatment as special cases.

Noise and efficiency limitations in a charge-coupled device are of vital importance in all kinds of applications. Because of problems with interface trapping, the buried-channel charge-coupled device (BCCD) has replaced the surface-channel charge-coupled device (SCCD). The potential minimum (the place where most of the electrons reside) is pushed away from the interface by means of doping. If the electrons are accelerated by high fields at some place they can still spill to the interface which causes noise and losses.

II. Theory

The rate equation for areal density of occupied interface states is given by

$$\frac{dN_{TS}}{dt} = (N_{TTS} - N_{TS})C_{ns}N_s - e_{ns}N_{TS} + r_s(t) \tag{2}$$

where N_{TTS} is the areal density of traps, $C_{ns}N_s$ and e_{ns} are the

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A Carrier Temperature Model Simulation of a Double-Drift IMPATT Diode

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Abstract—A computer simulation of double-drift silicon IMPATT diodes is presented. The model is essentially the conventional drift-diffusion model with two significant improvements; the ionization coefficients are assumed to be functions of carrier temperature rather than local electric field, and a description of the effects of the carriers' thermal conductivity is included [1]. Our model includes all known hot electron effects except velocity overshoot (hot electron drift, diffusion, relaxation, and heat conduction), and is exact within the framework of an electron temperature model.

THE PURPOSE of this paper is to report on the development of a set of computer programs which use a carrier temperature model including hot carrier heat conduction effects to simulate one-dimensional semiconductor devices in the time domain, and to report on early results of the application of this simulation to a double-drift silicon IMPATT diode. This type of diode has very high electric field gradients and rapid time variations, and these are the conditions under which the carrier temperature and heat conduction effects are expected to be significant [1]. A more detailed account of the simulation program, and further results will be presented at a later time.

In previous work, the large signal behavior of IMPATT diodes has been simulated by digital computer programs, which use finite difference methods to solve the well-known set of partial differential equations that govern charge transport [2], [3]. While work has been done to improve the accuracy and efficiency of the numerical techniques used to solve these equations [4], little work has been done to improve the simulation by using a more sophisticated set of partial differential equations, which incorporate other semiconductor phenomena in the device model. The application of the carrier temperature model to the simulation offers an opportunity for this type of improvement.

The carrier temperature model assumes that the spherical symmetrical part of the energy distribution f_0 of the carriers follows a standard Maxwell-Boltzmann distribution at the carrier temperature T_C which is greater than or equal to the lattice temperature T_L. The Maxwell-Boltzmann distribution plus the usual drift term f_1 is expected to be a fairly accurate approximation to the actual energy distribution of the carriers when strong carrier-carrier interactions are present. The high carrier concentrations in the active regions of an operating IMPATT diode justify to some extent the assumption of the same Maxwell-Boltzmann distribution for both electrons and holes. The equations for the current are used in the form derived by Stratton [5], which is most appropriate for the inclusion of hot electron phenomena. We give only the equations for electrons

$$j_n = qn\mu_n F + q\frac{\partial}{\partial x}(D_n n). \tag{1}$$

The equation of continuity is written as

$$\frac{\partial n}{\partial t} = G + \frac{1}{q}\frac{\partial}{\partial_x} j_n \tag{2}$$

where G is the generation rate (an expression for G is derived below), n is the electron concentration, D_n the diffusion constant, μ_n the carrier mobility, and F the electric field. Furthermore, we use the Poisson equation and the following equations for the electron temperature and ionization rate.

The equation for the carrier temperature has been given by Hess and Sah [6] for electrons (some of the derivation can be found in [5]), and when generalized to include both electrons and holes it becomes

$$\frac{\partial}{\partial t}[(n+p)\langle E\rangle] = (j_n + j_p)F + n\left\langle\frac{dE}{dt}\right\rangle\Big|_{n,\text{coll}} + p\left\langle\frac{dE}{dt}\right\rangle\Big|_{p,\text{coll}} + \frac{\partial}{\partial x}\left\{K\frac{\partial T_C}{\partial x} + \frac{1}{q}(j_n - j_p)\frac{\langle\tau E^2\rangle}{\langle\tau E\rangle}\right\} \tag{3}$$

where $\langle dE/dt\rangle|_{\text{coll}}$ indicates the energy loss rate of the respective carriers due to collisions (either ionizing collisions with other carriers or collisions with phonons), and K is the thermal conductivity, which is given by

$$K = 2k_B(D_n n + D_p p). \tag{4}$$

This can be derived as being analogous to Stratton [5]. k_B is Boltzmann's constant. For the Maxwellian distribution

$$\langle E\rangle = \tfrac{3}{2} k_B T_C \tag{5}$$

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Ballistic Electron Transport in Semiconductors

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Abstract—The possibility of ballistic transport in semiconductors is discussed and criteria are given for the experimental verification of ballistic behavior. The potential of purely ballistic motion, velocity overshoot, and inhomogeneities of the free carrier concentration in the space charge limited regime for device performance is assessed.

I. Introduction

THE IDEA of electrons lucky enough to escape collisions with crystal imperfections was first conceived by Shockley in context with impact ionization phenomena [1]. The semiconductor material of the early days, however, contained sufficient avoidable imperfections to make the collision rates of the order of 10^{14} s^{-1} and the mean free paths of the order of 10^{-7} cm. Current semiconductor materials are frequently so pure that only the unavoidable imperfections, the phonons, contribute to scattering, which brings the scattering rate to values of 10^{12} s^{-1} and less, for energies below the energy of optical phonons. Above this energy, the scattering rate is boosted to 10^{13} s^{-1} in practically all semiconductors because of spontaneous phonon emission [2]. In addition to the effects of nonequilibrium statistics, this steplike behavior of the phonon scattering leads to an overshoot of the electron velocity over its stationary value on short time scales or in inhomogeneous electric fields. This was first discovered by Ruch [3] and calculated for Si and GaAs by using Monte Carlo methods. It is clear that this effect can be used to enhance the speed of semiconductor devices if the device has a suitable field distribution. Since in small devices, charge neutrality is of minor concern (space charge limited range), the electric field is automatically inhomogeneous. The effect of an inhomogeneous field caused by space charge limited conditions was first added to the overshoot effects by Shur and then investigated in a large number of papers [4]-[6]. Recently, the claims in [4]-[6] have been subject to controversy [7]-[8]. It is the purpose of this paper to clarify the physical content of this controversy, to develop the basic concepts, and to assess the practical chances and use of purely ballistic transport.

II. Analytical Considerations

A. Homogeneous Fields and Carrier Density

Consider a number of free electrons which have a monoenergetic distribution (i.e., the energy distribution function is δ-like; the thermal broadening is neglected for the sake of simplicity). At time $t = 0$ we apply an electric field F which accelerates the electrons according to the well-known equations of motion. Close to the bandedge we may use the effective mass (m^*) approximation. As time progresses, electrons start to be scattered by crystal imperfections and by interactions among themselves. The electron–phonon scattering events and the electron–electron scattering events have two entirely different consequences. Since the electron–electron scattering conserves the total momentum and energy, it influences the electronic current only indirectly by establishing a distribution function, i.e., by broadening the monoenergetic starting distribution. This effect has been investigated, but not in enough detail to predict its consequences at the very beginning of the transient of the distribution function from the δ-form to its stationary value [9]. Qualitatively, the electron distribution develops with time as follows. In the initial stage the electrons move nearly ballistically. As soon as a substantial number of electrons has been scattered by phonons, the electron–electron scattering will do the rest and drive the distribution function to its stationary value. Thus far, investigations of ballistic transport barely accounted for electron–electron scattering, which will be enhanced by the space charge effects described in [4]. (In very small structures the electron densities are rather high because electrons are pulled out of the contacts.) Some of the previous treatments of ballistic transport are incorrect for two other reasons.

Shur and co-workers [4]-[6] used steady-state Monte Carlo results to obtain their characteristic time constants. This procedure implies a steady-state distribution function, which is very different from the true δ-like ballistic distribution at short times and distances. Therefore, they compute extremely high average electron energies (high speed) by using a distribution function with a substantial amount of electrons at low energies. As we will see at low energies, the scattering rate is significantly lower than at energies above the energy $\hbar\omega_{LO}$ of the optical phonons or above the energy when electrons can be scattered to other band extrema ($\simeq$0.3 eV for GaAs). Furthermore, in [4]-[6] the computations are applied to regions of the electron energy where the GaAs band structure is very nonparabolic. According to pseudopotential calculations [10], [11] the effective mass is already infinite or even negative for some of the highest energies computed in [4]-[6].

To obtain a better feeling for the numerical values of time constants and distances involved, consider the following equation (usually used in Monte Carlo simulations) for the time T which an electron moves without collisions:

$$\ln r = -\int_0^T \frac{1}{\tau}\,dt. \tag{1}$$

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Electrical Activation and Impurity Redistribution During Pulsed Laser Annealing of BF_2^+ Implanted Amorphized Silicon

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Abstract—Results of experiments studying the electrical activation and impurity redistribution during annealing of BF_2^+ implanted amorphized silicon with a *Q*-switched Nd:glass laser ($\lambda = 1.06$ μm) of 27.5 nm full-width half-maximum (FWHM) are presented. The experimental results are explained on the basis of a thermal melting model. The laser fluence necessary to initiate melting of the front surface was determined using time-resolved reflectivity measurements. The samples irradiated with laser fluences just below the melting threshold and with higher fluences producing melting to successively deeper regions inside the material were specifically investigated. It was found that for full electrical activation, the laser fluence should be large enough to melt past the original amorphous-crystalline interface and the underlying damaged layer, leading to liquid phase epitaxial regrowth and ~100 percent electrical activation.

INTRODUCTION

THE implantation of BF_2 molecular ions into Si is a useful method for acceptor doping, in which B provides the dopant and F accomplishes the amorphization [1]. The range statistics for molecular ion (BF_2^+) implants can be predicted by assuming that the BF_2 molecule splits into its components with energies apportioned by mass ratio. For example, a 150-keV BF_2 molecule results in two ^{19}F with 58 keV and one ^{11}B with 34 keV in the Si sample. BF_2 implanted Si, with fluence $\geq 1 \times 10^{15}$ cm^{-2}, has high electrical activation after low-temperature thermal annealing, and p^+-n junctions formed by BF_2^+ implants have low reverse leakage current. For the fabrication of devices requiring shallow p regions, BF_2^+ is easier to implant than B^+, since the implantation energy for BF_2^+ is much larger than that for B^+ to form identical boron range distributions, and more stable ion beam currents can therefore be obtained for BF_2^+ implants. Another advantage of BF_2^+ implantation is the amorphization provided by the heavier fluorine atom. Conventional thermal annealing at ~550°C results in regrowth of the amorphized layer, but does not electrically activate the tail of the B distribution, located below the original amorphous-crystalline interface [1]. Only in a thicker amorphous layer, formed for example by multiple Si^+ predamage implants, can the entire B profile be activated [1].

We have used the technique of pulsed laser annealing to activate electrically the B distribution by liquid phase epitaxial regrowth, thereby avoiding the complication of implanting B into a thicker amorphous layer produced by Si^+ implants. The mechanism of the laser-solid interaction during pulsed laser annealing is explained on the basis of a strictly thermal melting model [2], [3]. The laser fluence corresponding to the melting threshold is determined experimentally by time-resolved reflectivity measurements [2], [3]. The boron atomic distributions are determined by the secondary ion mass spectrometry (SIMS) technique. Differential resistivity and Hall effect measurements in conjunction with successive layer removal are used to obtain the electrical carrier distributions as a function of the laser fluence. We find that to obtain full electrical activation, the depth of melting must exceed the extended tail of the defect distribution, which is much deeper than the calculated value. The presence of such an extended defect distribution has been attributed to enhanced diffusion and partial channelling [4].

EXPERIMENTAL METHODS

Wafers of 4 Ω·cm phosphorus-doped (100) silicon were used in this investigation. BF_2^+ was implanted at room temperature at 150 keV to a dose of 1×10^{15} cm^{-2}. To reduce channelling effects, the implantations were performed a few degrees (~7°) away from the surface normal. This implantation produced an amorphous layer of thickness ~1325 Å, as determined by HF etching experiments [1].

Laser annealing was performed in air using a *Q*-switched Nd:glass laser ($\lambda = 1.06$ μm) with 27.5 ns full-width half-maximum (FWHM). The laser pulse energy was varied from 1.0 Jcm^{-2} to 4.0 Jcm^{-2} using absorbing filters. The melting threshold was determined by using a He-Ne laser to monitor the reflectivity of the front surface. Using a photomultiplier tube (EMI 9785B) of rise time 1.8 ns and a 400-MHz Tektronix transient digitizer, the transient signals were recorded. The melting threshold was experimentally determined to be larger than 1.0 Jcm^{-2}. Samples were annealed with laser fluences of 1.0, 2.5, and 4.0 Jcm^{-2} for study with the SIMS and the Hall effect measurements.

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0148-6411/81/1200-0425$00.75

TIME DEPENDENCE OF CURRENT AT HIGH ELECTRIC FIELDS IN $Al_xGa_{1-x}As$-GaAs HETEROJUNCTION LAYERS

Indexing terms: Semiconductor lasers, Semiconductors (III-V), Surface acoustic waves

Measurements of the current/voltage characteristics of layered $Al_xGa_{1-x}As$-GaAs heterostructures are presented. We show that under special circumstances surface acoustic waves can be amplified in these structures by surface acoustoelectric effects which might offer new device opportunities. In samples where the low field conduction occurs mainly in the GaAs, we observe at high fields short current peaks which we attribute to the modulation of the hot electron depletion layer width, which is consistent with the idea of real-space transfer.

It was shown in a series of papers[1-4] that semiconductor heterojunction layers can exhibit unusual properties in high electric fields. Electrons which first accumulate in the layers with smallest bandgap energies can be heated by electric fields to suprathermal levels and can then be thermionically emitted into the neighbouring material with a higher conduction band energy. It is clear that by suitable selection of doping, layer width, alloy composition etc. this effect can give rise to a new class of hot electron phenomena. The possibility of constructing Gunn-like devices with this electron transfer in real space (instead of k-space) has already been demonstrated.[4] In this letter we report two further phenomena associated with the introduction of bandgap discontinuities and layer boundaries. The first effect is the observation of peaks ($\sim$1 ns) at the beginning of the current pulses which we attribute to hot electron modulation of the interfacial depletion capacitance. The second effect, found only in samples with high doping in the top semiconductor layer, also shows a current peak at times between 1–200 ns. This peak, however, is attributed to the stimulated emission of surface acoustic waves, i.e. a modified form of the acoustoelectric effect.

Measurements were made on GaAs-$Al_xGa_{1-x}As$ ($0{\cdot}17 \leq x \leq 0{\cdot}2$) structures grown by molecular beam epitaxy (MBE) on semi-insulating GaAs substrates. The top layer was $Al_xGa_{1-x}As$ with a doping density of $N_D \simeq 10^{17}$ cm^{-3} and was 0·1 μm thick. The GaAs layer underneath was not intentionally doped and ranged in thickness from 0·07 μm to 1·6 μm. It was sandwiched between the top doped and a second (undoped) $Al_xGa_{1-x}As$ layer in some of the samples. The mobility in the GaAs layers was enhanced over the bulk value for equivalent doping and was around 20 000 cm^2/Vs at 77 K. The doped AlGaAs layer had a mobility of about 1500 cm^2 Vs. Most of our knowledge of carrier concentration and mobility

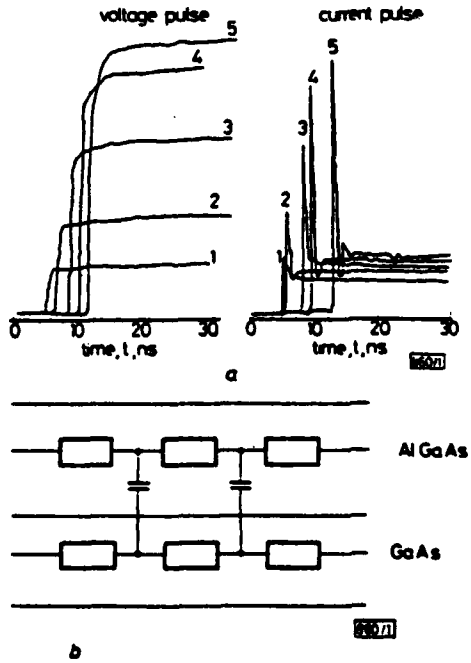

Fig. 1

a Leading edges of voltage pulses and corresponding current pulses for electric fields of (1) 1·5 kV cm, (2) 2·7 kV·cm, (3) 5·0 kV/cm, (4) 7·3 kV/cm and (5) 8·1 kV/cm

b Sample geometry showing AlGaAs and GaAs layers and equivalent circuit containing depletion layer capacitance

was obtained from Hall effect data, which reflect only average concentrations and mobilities for the sample. Au-Ge contacts were evaporated on the top layer ($Al_xGa_{1-x}As$) and alloyed by heating at a rate of 400°C/min in flowing H_2 to a final temperature of 450°C. These contacts were found to be ohmic in most cases. The distance between contacts was 0·065 cm and the width of the samples was approximately 0·08 cm. The experiments were performed using 600 ns voltage pulses and the measurements of the current/voltage characteristics were taken at times between 1 ns and 600 ns. The samples were mounted in GR insertion units and a 50 Ω sampling oscilloscope and *x-y* recorder were used to obtain the current/voltage characteristics.

Fig. 1*a* shows the shape of the current pulses at various electric fields. Within the first nanosecond there appeared a peak in numerous samples which was only weakly dependent on the sample resistance and was not caused by the external circuit (a dummy resistor of the same resistance did not show a peak). This peak was also only weakly dependent on temperature and was observed at both 300 K and 77 K. The peak does, however, depend on the applied voltage and appeared in some samples only above the threshold for real space transfer (i.e. was correlated to the appearance of current saturation and/or negative differential resistance). We attribute this peak to changes in the depletion layer capacitance at the AlGaAs-GaAs interface. As soon as electrons transfer back from the GaAs to the AlGaAs the depletion layer width is reduced and the capacitance increases. Our experimental conditions were not sufficiently definitive to evaluate this effect quantitatively as can be seen from the sample geometry and equivalent circuit in Fig. 1*b*. It is clear that inhomogeneities of the resistance, contact effects etc. can influence the measurements in this geometry and a quantitative experiment should measure the transverse capacitance separately. Note, however, that this effect represents a new kind of voltage variable capacitance. It should also be noted that this effect is not present in bulk GaAs.

In some samples in which the AlGaAs was so highly doped that it made the main contribution to conduction, a *current* peak of a different kind was observed at early times (1–200 ns) as shown in Fig. 2. This peak was also linked to a negative differential resistance (NDR). This NDR, however, occurred at 77 K only and at much lower electric fields ($F \simeq 300$ V/cm)

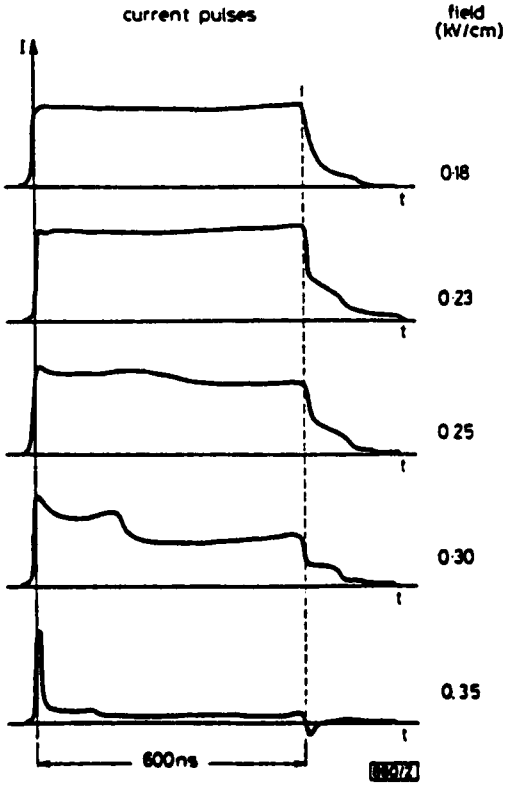

Fig. 2 *Current pulses exhibiting a second form of initial peak and decreasing current with increasing electric field. This effect is attributed*

than the NDR observed in connection with real space transfer.[1] The AlGaAs mobility of our samples was about $\mu = 1500$ cm²/Vs, which makes $\mu F \simeq v_s$, the longitudinal sound velocity in AlGaAs. This fact, together with the dependence of the long incubation time of the current drop on the electric field and the disappearance of the effect at 300 K for our sample length (higher lattice losses) strongly suggests an explanation by the acoustoelectric effect. In contrast to the bulk acoustoelectric effect, however, we amplify the sound waves in a layer of ~ 1000 Å near the surface, which determines the frequency of the amplified surface waves to be ~ 10 GHz.[5] It is worth mentioning that this presents a possibility of direct generation of surface acoustic waves which might be far superior to the bulk acoustoelectric effect because of the versatility of the MBE crystal growth and the smallness of the structures, which can be made of the order of the coherence length of the generated sound. One can therefore avoid the incoherent amplification as it is usually found in bulk material.

In summary, we report two new features of heterojunction transport. One is the hot electron control of the depletion capacitance, and the second is the generation of surface acoustic waves.

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Lateral Transport in Superlattices

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Abstract. - Theoretical and experimental results are presented for lateral transport in layered heterojunction structures. It is shown that the variability of boundary conditions (periodic or nonperiodic) gives rise to a series of novel effects with high device potential. These effects will be presented stressing the real-space - k-space analogy.

1. Introduction. - When I heard in 1977 C. Hilsum's "Look Over The Shoulder" presented at the meeting in Denton [1], I did not realize that two years later I would almost experience another direct proof of his last quotation from Hegel [2]. In 1979 Hadis Morkoç, Ben Streetman and myself were led to the idea of real space transfer in superlattices [3], an effect which inter alia can be used to produce the real space analogy of the Gunn effect in properly designed samples. We performed some preliminary calculations of this effect and submitted a manuscript [4] which was characterized by the first referee as unimportant, incomplete, and mostly wrong. We would have stopped the work on this project, if we had not obtained confirmation of our estimates by sophisticated Monte Carlo calculations performed by Glisson et al. [5] and calculations with the method of moments by Shichijo et al. [6] as well as encouragement by discussions with J. Bardeen and H. Kroemer.

Meanwhile we also learned more about already well known variations of the real space transfer effect. Among these variations are the electron emission from silicon into silicon dioxide which was discovered by Ning [7], the transfer of electrons to a floating gate in read only memories and the diffusion of hot electrons in graded gap semiconductors measured by Dargis et al. [8]. Superlattices and small quantum well heterostructure layers add many possibilities to these effects. In fact, a general correspondence of $\vec{k}$-space and real space transport effects can be established. It is the purpose of this paper to describe the lateral transport in superstructures and to illustrate this $\vec{k}$-space real-space correspondence on the basis of concrete examples.

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HOT ELECTRONS IN LAYERED SEMICONDUCTOR STRUCTURES AND HETEROSTRUCTURES

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1. INTRODUCTION

Parallel to the revolutionary development of large scale integrated silicon technology much progress has been made in the technology and basic physical understanding of artificial crystals, superlattices and, generally, lattice-matched semiconductor heterostructure layers. For example, heterostructure lasers (including superlattices) with low threshold currents and flat temperature dependence have been successfully grown using metalorganic chemical vapor deposition (MO-CVD), molecular beam epitaxy (MBE) and liquid phase epitaxy (LPE)[1-3]. It has also been possible to produce layered structures exhibiting extremely high carrier mobility using the technique of modulation doping [4]. These technological advances are presently stimulating large scale research.

In this review we describe common features of both metal-oxide-silicon

(MOS) devices and III-V lattice-matched heterostructure layers. These common features are connected with the two-dimensional nature (size quantization) in these structures and with "suprathermal" excitation of the electrons by high electric fields or by optical pumping. We concentrate on spatial redistribution of electrons, or real-space transfer. The real-space transfer of electrons is caused by carrier redistribution to the position of lowest kinetic energy of the heterostructure. This process occurs, of course, by phonon emission as the system attempts to achieve equilibrium. Optical or electrical excitation can lead to the inverse, i.e., carrier excitation and transfer. This can have a detrimental effect on certain kinds of device operation, but can give rise also to ultra-fast switching phenomena. In addition to these effects caused by boundaries and by space charge build-up, pronounced effects are observed owing to small layer sizes. The power/volume ratio in ultra-thin-layer structures can be extremely large and create new effects. Some of these will be discussed in connection with quantum-well heterostructure (QWH) lasers.

Comments on the plasma annealing model to explain the dynamics of pulsed laser annealing of ion-implanted silicon

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Experimental problems are discussed associated with optical transmission and Raman spectroscopy measurements during pulsed laser annealing of silicon. In view of these problems, the use of these experiments in support of a plasma annealing model is questioned.

PACS numbers: 78.30.Gt, 65.90. + i, 64.70.Dv, 61.70.Tm

Many phenomena resulting from pulsed laser annealing of ion-implanted silicon can be explained on the basis of a thermal melting model.[1,2] There have, however, been interesting theoretical considerations by Van Vechten *et al.*[3] about the possible role of screening effects in the dense electron-hole plasma which might prevent the lattice temperature from rising significantly during pulsed laser annealing of silicon. Experimental results using time-resolved transmission measurements[4] and Raman spectroscopy[5] are cited to support the plasma annealing model. The purpose of this comment letter is to point out difficulties in the interpretation of these two measurements for studying typical pulsed laser annealing experiments and to propose additional experiments suitable to this problem.

In the transmission experiments, Lee *et al.*[4] use a Ge detector located behind the Si sample to monitor light from a probe laser transmitted during the annealing laser pulse. Since transmitted light is not entirely quenched during the laser pulse and subsequent period of altered surface properties, they conclude that the surface could not have melted. The problem with this experiment is that the probe laser is not the only possible source of transmitted light. If, for example, the front surface reaches a very high temperature as is generally believed,[1,2] considerable blackbody radiation is emitted. The Ge detector would then respond to photons between its own band gap and that of the Si sample through which the radiation is transmitted. In addition, there may be some Si photoluminescence at the very high electron-hole concentrations of this experiment. Therefore, a broad-band observation of transmitted light during an annealing pulse cannot be used to conclude that the front surface does not melt. One might, however, monitor emitted wavelengths not otherwise present in the experiment to study the temperature transient by blackbody radiation.

The second experiment (Raman Spectroscopy[5]) measures the nonequilibrium phonon occupation number at small phonon wave vectors $q \lesssim 10^5 \text{cm}^{-1}$. This experiment was used by Lo and Campaan[5] to conclude that the Si surface temperature does not rise above several hundred degrees centigrade during the experiment. The phonons generated by excited electrons (or holes), however, have a minimum wave vector of[6]

$$|q_{\min}| = |\mathbf{k}|[(1 + \hbar\omega_{\text{opt}}/E)^{1/2} - 1]$$

Here $\mathbf{k}$ is the wave vector of the electrons, E is their energy, and $\hbar\omega_{\text{opt}}$ is the energy of the predominantly optical phonons generated. Typically we have $q_{\min} \gtrsim 10^6 \text{cm}^{-1}$. The decay of these phonons towards thermal equilibrium occurs in many steps and some of the phonon modes involved in this decay survive for considerable time and over macroscopic distances.[7] Also, the phonons having the longest wavelength are heavily screened. It is therefore not at all clear that the Raman experiment gives conclusive evidence about the state of excitation of the vibrational spectrum, since the measured Stokes/Antistokes amplitude ratio may not have reached the steady state.

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Demonstration of a new oscillator based on real-space transfer in heterojunctions

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A new real-space transfer oscillator is demonstrated in a layered GaAs/*n*AlGaAs heterojunction. A dc bias field, plus the ac oscillating field, is applied parallel to the layer interfaces to modulate the electron transfer from the GaAs layers to the *n*AlGaAs layers. This periodic electron transfer results in the ac current being 180° out of phase with the ac voltage and power being generated. A unique characteristic of this oscillator is that the electron transit times are associated with transverse dimensions and not dimensions between the ohmic contacts which should permit its extension to very high frequencies.

PACS numbers: 72.20.Ht, 72.80.Ey, 72.20.Jv

In this letter it is demonstrated that if a dc plus ac electric field is applied parallel to the layered interface of a heterostructure, a new type of conduction current oscillator making use of real-space transfer[1] has been realized.

The principle of oscillation can be explained with the aid of Fig. 1 which depicts a three-layer GaAs-nAl$_x$Ga$_{1-x}$As heterostructure with a dc and ac bias applied parallel to the layered interface. The applied voltages will cause dc and ac heating of the electrons in the low resistance GaAs layer periodically moving them between the GaAs layer and the high resistance nAl$_x$Ga$_{1-x}$As layers. This will result in the ac current being 180° out of phase with the ac voltage to achieve power generation.

A particularly interesting aspect of this conduction current oscillator is that the electron "transit times" are associated with transverse dimensions of the structure and not distance between the ohmic contacts.[1] Here the GaAs layer can be made quite thin (50–200 Å) so that the hot electrons have a small distance to travel to reach the n-type Ga$_{1-x}$As layers.

The J-ξ (current density, electric field) characteristics of these layered GaAs/nAl$_x$Ga$_{1-x}$As structures have been studied by Hess,[1] Shichijo,[2] Keever[3] and colleagues, and the enhanced mobility by Dingle *et al.*[4] and Morkoç and colleagues.[5] These studies confirm the transfer of electrons from their parent donors (in the Al$_x$Ga$_{1-x}$As) to the GaAs and support the reverse transfer back to the Al$_x$Ga$_{1-x}$As by high-field heating of the electrons.

The "three-period" GaAs/nAl$_x$Ga$_{1-x}$As heterostructure used in the experiments is shown in Fig. 2. This structure had an undoped Al$_x$Ga$_{1-x}$As buffer layer to further enhance the mobility in the GaAs, but it is believed that this is not necessary for the oscillator application.

A tunnel diode rf circuit,[6] shown in Fig. 3, was used to study the oscillator behavior in the 2–25-MHz range for convenience in oscilloscope measurements. The heterostructure was mounted in a transistor header which was placed in liquid nitrogen. Pulsed voltages in the 1–5-μs range at low repetition rates of 60–100 Hz were employed to avoid heating the device appreciably. The heterostructure sample dimensions were 1-mm width with 50-μm metal contact spacing.

An I-V curve of the three-period sample is shown in Fig. 4. It is seen that the current saturates around 10 V and displays a slight negative slope for voltages of 10–25 V.

Oscillator traces of the oscillator behavior and waveforms are displayed in Fig. 5. In (a) and (b), the LC circuit was tuned to 2 MHz while in (c) and (d), the LC circuit was tuned to 25 MHz. As seen in Figs. 5(a) and 5(b), as the pulsed bias voltage is increased, one first sees a small highly damped ringing of the LC circuit at the start of the trace, then as threshold is approached the damping decreases, the ringing increases and in Fig. 5(b) steady-state oscillation is achieved with further increase in bias. The behavior at 25 MHz is identical to that at 2 MHz with the bias voltage near 13 V and the peak rf voltage near 3 V. Increasing the dc bias beyond 13 V did not appreciably increase the peak rf voltages.

These real-space transfer oscillator characteristics are to be contrasted to those of a Gunn oscillator. In the traveling dipole domain mode ($nl > 2\times10^{12}$ cm^{-2}) a Gunn oscillator shows little response to circuit tuning as demonstrated for example by Hakki and Knight.[7] Here the real-space

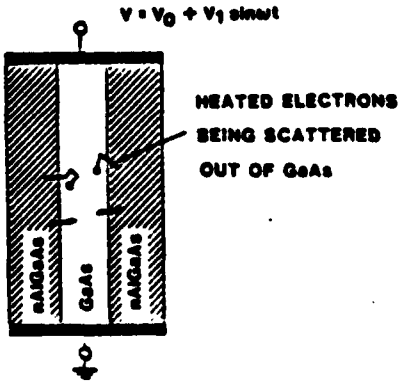

FIG. 1. Periodically heated electrons moving in and out of GaAs layer in heterojunction.

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Solid-State Electronics 25, 491 (1982).

Resonance Impact Ionization in Superlattices

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ABSTRACT

We propose an enhancement of the electron or hole impact ionization coefficients (α or β) by introducing resonant impact ionization states into the (conduction or valence) band by using suitable lattice matched multilayer heterojunctions (superlattices). Model calculations for the AlAs:GaAs superlattice indicate resonance enhancements can occur over a wide range of energy gaps (1.54 - 1.9 eV). The gap can be varied by choosing the appropriate ratio of the alternating layer thickness. This effect should be useful for improving the signal/noise ratio of avalanche photodiodes significantly.

Appl. Phys. Lett. 41, 664 (1982).

Theory of resonant scattering in semiconductors due to impurity central-cell potentials

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ABSTRACT

The effects of scattering by the central-cell defect potential of a substitutional sp^3-bonded impurity or vacancy in a zincblende host are evaluated. Significant scattering of electrons can occur if a "deep resonance" lies slightly above the conduction band edge. The theory is applied to scattering of electrons by defects in GaAs.

PACS Numbers: 72.10.-d; 72.10.Fk; 72.80.Eg

In Advances in Electronics and Electron Physics, ed. by P. W. Hawkes, Vol. 59, p. 239 (New York: Academic Press, 1982).

ASPECTS OF HIGH FIELD TRANSPORT IN SEMICONDUCTOR HETEROLAYERS AND SEMICONDUCTOR DEVICES

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Numerous papers, reviews and books have been written on high field transport in semiconductors and semiconductor devices (see e.g. Landau and Kompanejez (1934), Shockley (1951), Hilsum (1962), Ridley and Watkins (1963), Gunn (1963), Conwell (1967), and Ferry et al. (1980). One can safely say that the theoretical aspects of high field transport in bulk semiconductors under steady state conditions are understood in great detail within the semiclassical Boltzmann formulation for electric fields $F \lesssim 10^4$ V/cm. The basic principles have been established and their treatment has been simplified to such an extent that a wide variety of phenomena can be calculated to an accuracy of a factor of 2 or so with a pocket calculator.

This review concentrates on new developments in the general area of high field transport and is also intended to provide a bridge in the information gap between scientists working on device modeling and others working on the basic physics of hot electrons.

Abstract for an Invited Paper

for the Philadelphia Meeting of the

American Physical Society

November 3-5, 1982

Electronic Transport in GaAs-GaAlAs Heterolayers and High Mobility Transistors.*

K. HESS, University of Illinois, Urbana. (30 min.)

Lattice matched semiconductor heterojunctions have been widely used in semiconductor lasers, photodetectors, solar cells and bipolar devices. Two new epitaxial technologies have emerged in recent years (metal-organic-chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE)) and have added a variety of new possiblities[1] including the fabrication of MESFET-high mobility transistors (HMET)[2] and double semiconductor metal insulator transistors (MISS-transistors).[3] A general survey of new transport effects at low and high electric fields in heterostructure layers will be given with special emphasis on the possibility of achieving extremely high mobilities and on high field real space transfer.[4] The opportunities and disadvantages of these effects for constructing novel devices are discussed using the HMET, the MISS-transistor as well as real space transfer and optoelectronic devices (e.g., the superlattice avalanche-photodiode) as an example. It is concluded that the variability of boundary conditions offers fascinating and physically highly interesting possibilities for novel device concepts.

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ELECTRON TRANSPORT IN HETEROJUNCTIONS AND SUPERLATTICES

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ABSTRACT

Theoretical and experimental results are presented for high field transport in heterojunction structures parallel to the layers. It is shown that these structures exhibit new transport effects with high potential for device applications. A novel oscillator principle and novel storage and switching phenomena are described. These effects are 'real-space' analogies to well-known k-space effects such as the Gunn effect.

Proceedings of the 16th International Conference on the Physics of Semiconductors, 1982 (invited paper).

THEORETICAL AND EXPERIMENTAL STUDY OF SWEPT LINE ELECTRON BEAM ANNEALING OF SEMICONDUCTORS

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ABSTRACT

The temperature distribution in a rectangular sample as a function of time and position during swept line electron beam (SLEB) annealing has been calculated. Beam penetration effects have been included by using the Monte Carlo method and the temperature distribution has been obtained from Green's function techniques and the method of images. The effects of various beam parameters on the temperature distribution have been studied. The results are correlated with experimental studies of the electrical activation of Be in GaAs during SLEB annealing. The annealing is shown to be governed by a relation of the form

$$\text{Activated fraction} = (\text{Dwell time}) \times \left(3840\, e^{-\frac{0.535}{k_B T}}\right).$$

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(in preparation)

Annealing studies of laterally seeded recrystallized silicon on silicon dioxide. I. Phosphorus implants

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ABSTRACT

Phosphorus implantation studies of laterally seeded silicon on silicon dioxide recrystallized by a scanning graphite strip heater are presented. Hall profiling has been used to obtain donor concentration and electron mobility as a function of depth. The recrystallized silicon layer contains subgrain boundaries which slightly reduce phosphorus activation and electron mobilities below bulk silicon values.

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(in preparation)

Annealing studies of laterally seeded recrystallized silicon on silicon dioxide. II. Boron implants

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ABSTRACT

Microzone melting by a moving graphite strip heater has been employed to recrystallize polysilicon on silicon dioxide layers. Electrical activation and hole mobilities in boron implanted silicon-on-oxide have been measured by the double a.c. Hall effect method. Comparative studies with bulk silicon and unrecrystallized polysilicon show that these recrystallized silicon films have excellent electrical properties.

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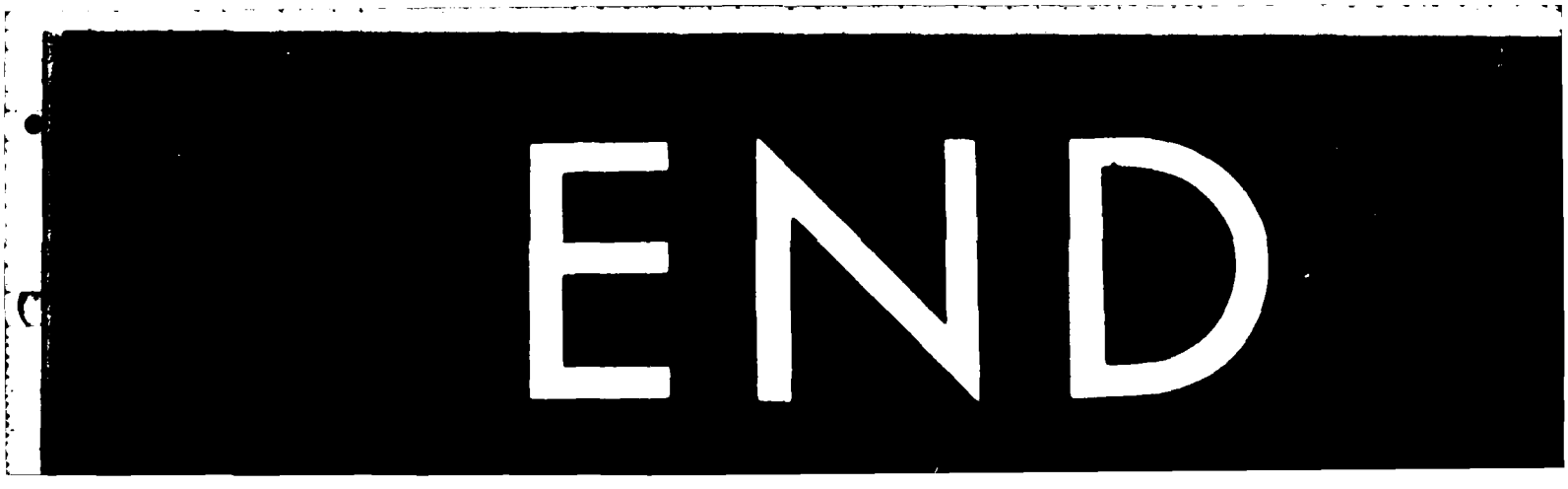
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